TPC R&D for an ILC Detector

Status Report from the LC-TPC groups [1] [2]

LC-TPC groups

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Abstract

This report of April 2006 gives an update of TPC studies since the review in October 2004, available at http://www.desy.de/f/prc/. The R&D described is related to the the LC-TPC design criteria which are enumerated in the Appendix. Representative (preliminary) results from various groups are presented here as examples of the work going on.

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[1] Proposal PRC R&D-01/03 of the DESY Physics Review Committee. The present status report is submitted for the DESY PRC Meeting of 11/12 May 2006.

[2] The WWSOC, the Organising Committee for the World-Wide Study on Physics and Detectors for the Linear Collider has formed a subcommittee for following LC Detector R&D activities globally. The work related to the LC-TPC can be found at https://wiki.lepp.cornell.edu/wws/bin/view/Projects/TrackLCTPCcollab. This report is intended for any of the review committees within the WWS.

[3] A group from U Siegen will participate if their research grant is approved.

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1 Introduction

A detector at a the International Linear Collider (ILC) will combine a tracking system of high precision and granularity with a calorimeter system of very high granularity. This detector, an example of which is proposed in the TESLA technical design report[1], will measure charged tracks with an accuracy surpassing the precision of previously built detectors at LEP, the Tevatron, HERA, RHIC or the LHC by a factor of ∼10. In addition the detector will be optimized for the reconstruction of multi-jet final states stressing the jet energy resolution and the reconstruction of individual particles in jets. For the latter efficiency and reliability in reconstructing charged tracks is more important than precision.

A typical design of a "large" detector is the LDC – Large Detector Concept[2] – or the GLD – Giant Large Detector[3] – which have tracking systems consisting of a large TPC as central tracker combined with silicon detectors for vertexing, barrel and forward tracking.[12]

In a previous document[5] the LC-TPC groups proposed to investigate the feasibility of designing and testing the TPC technology for this collider. To this end an R&D program was approved by the DESY PRC in 2001 and reviewed again in April 2003 and October 2004; the last report is available at [6]. In this paper we report the present status of the R&D work and elaborate the next steps towards a full demonstration of the technology.

2 R&D program for the LC-TPC

The requirements for a TPC at the ILC and the issues are summarized in the Appendix (Section 8). TPCs have been used in a number of large collider experiments in the past and have performed excellently. These TPCs were read out by wire chambers. The thrust of this proposal is to develop a TPC based on micro-pattern gas detectors (MPGDs), which promise to have better point and two-track resolution than wire chambers and to be more robust in high backgrounds. Systems under study at the moment are Micromegas[7] meshes and GEM (Gas Electron Multiplier)[8] foils. Both[9] operate in a gaseous atmosphere and are based on the avalanche amplification of the primary produced electrons. The gas amplification occurs in the large electric fields in MPGD microscopic structures with sizes of order 50 μm.

The operational conditions at the linear collider – long bunch trains, high physics rate – require an open gate operation without the possibility of intra-train gating between bunch-crossings should the delivered luminosity be optimally utilized. (Inter-train gating between bunch trains is possible and recommended as explained in the Appendix.) MPGDS lend themselves naturally to the intra-train un-gated operation at the ILC since they can operate with a significant suppression of the number of back-drifting ions.

The R&D program proposed four years ago is in the process of addressing the novel issues which include the following (see [5] for more details).
-Operate MPGDs in small test TPCs and compare with wire gas amplification to prove that they can be used reliably in such devices.
-Investigate the charge transfer properties in MPGD structures and understand the resulting ion backflow.
-Study the behaviour of GEM and Micromegas with and without magnetic fields.
-Study the achievable resolution of a MPGD-TPC for different gas mixtures and carry out

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[12] In addition there is a 4th detector concept[4] with unusual calorimetry being studied which also foresees a TPC as central tracker.

aging tests.
-Study ways to reduce the area occupied per channel of the readout electronics by a factor of at least 10 compared to e.g. the STAR TPC[10] with a minimum of material budget.
-Investigate the possibility of using Si-readout techniques or other new ideas for handling the large number of channels.
-Investigate ways of building a thin field cage which will meet the requirements at the ILC.
-Study alternatives for minimizing the endplate mechanical thickness.
-Devise strategies for robust performance.
-Pursue software and simulation developments needed for understanding prototype and the LC-TPC performance.

3 R&D strategy

To meet the above goals, the institutes listed on this report joined together as LC-TPC groups, with the aim of sharing information and experience in the process of developing a TPC for the linear collider, and of providing common infrastructure and tools to facilitate these studies. This R&D work is proceeding in three phases:
-(1)Demonstration Phase: Finish the work on-going related to many items outlined in the preceding paragraph using "small" ($\phi \sim$30cm) prototypes, built and tested by many of the LC-TPC groups listed on this document. This work is providing and will continue to provide a basic evaluation of the properties of an MPGD TPC and demonstrating that the requirements outlined above and in the Appendix can be met.
-(2)Consolidation Phase: Design, build and operate a "Large Prototype" (LP). By "Large" is meant ~1m diameter, i.e., the detector is significantly larger than the current prototypes, so that: first iterations of TPC design-details for the LC can be tested, larger area readout systems can be operated and tracks with a large number of measured points are available for analyzing the various effects.
-(3)Design Phase: Start to work on an engineering design for aspects of the final detector. This work in part will overlap with the work for the LP, but the final design can only start after the LP R&D results are known.

3.1 Executive summary of what has happened to date.

Up to now during Phase(1),
-3 to 4 years of MPGD experience has been gathered,
-gas properties have been rather well understood,
-diffusion-limited resolution is being understood,
-the resistive foil charge-spreading technique has been demonstrated,
-CMOS pixel RO technology has been successfully demonstrated and
-design work is starting for the LP.

3.2 Next R&D steps

The small-prototype work will continue for the next couple of years in parallel with Phase(2), the consolidation of the efforts via the construction and operation of the LP. It will be carried out in conjunction with the EUDET facility[11] which is also starting and will provide the infrastructure for performing LC detector R&D. The LP work is expected to take about four years and will be followed by Phase(3), the design of the LC-TPC.

Finally, to summarize briefly the planning for the LC-TPC and the LP, the tasks have been broken down into “LC-TPC/LP Workpackages” below, and the tasks have been distributed among the LC-TPC groups listed on this report. These workpackages are set up for building the EUDET facility and performing the R&D relevant to the design of the LC-TPC outlined in the Appendix.

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         Workpackage:                                     Groups involved:

Workpackage (0) TPC R&D Program                  LC-TPC collaboration
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Workpackage (1) Mechanics
-------------------------
 a) LP design (incl. endplate structure)       Cornell,Desy,MPI,IPNOrsay,
                                                 +contribution from Eudet
 b) Fieldcage, laser, gas                      Aachen,Desy,St.Petersburg,
                                                 +contribution from Eudet
 c) GEM panels for endplate               Aachen,Carleton,Cornell,Desy/HH,
                                                   Kek/XCDC,Victoria
 d) Micromegas panels for endplate              Carleton,Cornell,Kek/XCDC,
                                                     Saclay/Orsay
 e) Pixel panels for endplate             Freiburg,Nikhef,Saclay,Kek/XCDC,
                                                 +contriubution from Eudet
 f) Resistive foil for endplate             Carleton,Kek/XCDC,Saclay/Orsay

Workpackage (2) Electronics
---------------------------
 a)"Standard" RO/DAQ sytem for LP             Aachen,Desy/HH,Lund,Rostock,
                                                   Montreal,Tsinghua,
                                                  +contribution from Eudet
 b) CMOS RO electronics                            Freiburg,Nikhef,Saclay,
                                                  +contribution from Eudet
 c) Electronics, power switching, cooling for LC-TPC
                                              Aachen,Desy/HH,Lund,Rostock,
                                          Montreal,St.Petersburg,Tsinghua,
                                                  +contribution from Eudet


Workpackage (3) Software
------------------------
 a) LP software +
    simul./reconstr.framework          Desy/HH,Freiburg,Carleton,Victoria,
                                                  +contribution from Eudet
 b) LC-TPC simulation/perf., backgrounds  Aachen,Carleton,Cornell,Desy/HH,
                                          Kek/XCDC,St.Petersburg,Victoria
 c) Full detector simulation/performance           Desy/HH,Kek/XCDC,LBNL
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Workpackage (4) Calibration

a) Field map for the LP	Contribution from Eudet
b) Alignment	Kek/XCDC
c) Distortion correction	Victoria
d) Radiation hardness of materials	St.Petersburg
e) Gas/HV/Infrastructure for the LP	Desy, Victoria, +contribution from Eudet

4 Developments

Some R&D developments related to the LC-TPC design issues in Section 8 will be reviewed next.

4.1 Facilities

A number of test facilities have become available over the last few years for TPC studies.

First the *magnets* will be described.
-At DESY a high-field magnet test stand was commissioned in late 2002 which provides magnetic fields of up to 5.3T in a volume of 28 cm diameter by 60 cm length. This magnet is equipped with a cosmic ray trigger, and a UV laser was added to allow high rate and multi-track measurements. This magnet has been used by ∼8 groups for tests of prototypes with GEMs or MWPCs. In addition a 1T magnet in a test beam (see below) was used.
-A 2T, 53 cm-bore magnet with homogeneous field was available at Saclay and used for studies of Micromegas TPCs with cosmics.
-At KEK two coils with 85 cm-bore, one with 1.2T for beam tests and the other with 1.5T for cosmic tests, were employed. The former was "thin-walled" (20% X_0) so that the test beams could penetrate the side of the coil into the TPC volume with little degradation. This coil, PCMAG (earlier known as JACEE), will be used in future for the EUDET facility[11].

The *test beams* were as follows.
-At KEK the groups have been using a test beam with momentum up to 4 GeV/c and PID capabilities for TPC measurements with electrons, pions, kaons and protons.
-One group has performed extensive prototype tests at a hadronic test beam at CERN.
-DESY provides an electron test beam of up to 6 GeV electrons was used by several TPC groups. The studies employed a 1T magnet and a Si telescope. The beam will be used for the future EUDET program and equipped with the PCMAG from KEK (see above).

Finally, several groups have set up and are operating small *cosmic-ray* test stands, which have been used to establish operational procedures and measurements for their prototype chambers.

4.2 Gas-amplification systems

A central part of the R&D activities for a LC-TPC is the investigation of different types of MPGDs. The GEM foils have been produced mainly at CERN[9] up to now, while foils from other manufacturers (in Germany, Japan, Russia and the USA) were tested as well. Also Micromegas were made by the CERN workshop; the lastest development was that of so-called bulk Micromegas, where the padplane, pillars and mesh are integrated into a single unit using a manufacturing procedure involving additional steps, and good results were achieved. Recently US groups have access to both GEM foils and Micromegas produced by the 3M company. In general the performance of MPGDs made by different manufacturers has been comparable, CERN being somewhat better up to now.

4.3 Prototype TPC chambers

To gain experience and explore potential improvements, a number of different prototype TPCs have been built by ~12 of the groups and tested in collaboration with other groups. The chambers were built to fit inside the high field test facility at DESY, the magnet at Saclay or that at KEK, to test out some first ideas about the mechanical and electrical structure of a possible future TPC. These chambers typically have diameters of 30 to 50 cm and drift lengths of up to 1 m.

To provide a direct comparison of MPGDs, two chambers were constructed, one at MPI/DESY/KEK[12] and the other at Cornell/Purdue[13], for which endplates with all four options, MWPC, GEM, Micromegas and the resistive-foil technique (below, Section 5.5), are being tested (some results are in Section 5). These two chambers plus the prototypes mentioned in the previous paragraph will provide valuable cross-checks on performance of the different options.

The evaluation of the performance of all above prototypes will feed into the ensuing R&D program at the EUDET facility, where the definitive tests for the LC-TPC technology decisions will be carried out.

4.4 Fieldcage

An important function of the field cage is to maintain as homogeneous a field as possible and be as thin as possible. Simulations have been carried out to optimize the structure of field forming strips. It is known that the most homogeneous field can be achieved if the complete area of the field cage is covered with strips. Therefore the current design foresees strips on the inside and on the outside of the insulating layer, staggered by half a width of the strips. A uniformity of better than $\delta\mathrm{E}/\mathrm{E} = 10^{-4}$ seems achievable. Currently work is underway to study the influence of possible field inhomogeneities on the overall resolution of the TPC.

As for the thinness, the structures for the field cage investigated are composite structures. A high tensile shell made from either carbon fibre or glass fibre and epoxy composite is glued to a shell of very light honeycomb material. On the inside a layered structure of a highly insulating material like Kapton or Mylar provides HV insulation and the surface on which the electrodes for the field cage are mounted.

Two prototype field cages were built along these principles. They differ in that one uses carbon-fibre and the other glass-fibre as structural material and in the way in which the resistive divider is mounted in the chamber. Currently experiments are under way to commission these field cages and to understand their properties. In future these techniques can be further developed and others tried at the EUDET facility.

4.5 Mechanics

A central part of a MPGD TPC is the structure of the readout endplate. For the prototype TPCs built so far no attempt was made to optimize the support structures for MPGD, nor has special attention been paid to minimize the material budget. Work has started for the next generation of prototypes at EUDET to develop a first realistic model of an endplate. In collaboration also with groups from the calorimeter R&D efforts within the linear collider community, studies are underway about the production and support of large area MPGDs.

4.6 Electronics

An important part of the development of an LC-TPC is going to be the development of high density low-power electronics that will allow a thin endplate ($< 30\%$ X_0) to be built.

Recently work has started on a development of a first dedicated electronics version for the LC-TPC. It takes advantage of the fast MPGD signals and is highly integrated. The Preshape 32 has been chosen as the front-end, providing 32 channels on one chip with a nominal peaking time of 45 ns [14]. It is planned to follow this with a 10bit ADC running at at least 40 MHz sampling speed.

An alternative development has been the investigation of a TDC based system for the readout of a TPC. The idea is based on charge-sensitive readout electronics, equipped with a charge-to-time conversion circuit and multi-hit TDC for each channel. It has been demonstrated that it is feasible to operate this new type of readout electronics with a TPC detector based on GEM, and performance studies are ongoing.

The LP work planned for EUDET will adapt the ALTRO chip designed for the ALICE experiment[15] in order to have a large number of channels available for the tests. In addition, the ideas in the preceding two paragraphs will be tried out.

In future the readout-density requirement, which is discussed in the Appendix and is mainly an ASICs problem, appears solvable because deep sub-micron technology is now avaiable (STAR used 3.2-micron technology). The power problem also appears solvable since one can take advantage of the time structure of bunch crossings at the ILC to ramp down the power between bunch trains. Dedicated work on a final electronics design for the LC-TPC utilizing these aspects has not yet started, but a first iteration will begin soon at part of the LP/LC-TPC workpackages, Section 3.2.

4.7 Si-based TPC-readout concepts

The TPC as proposed for the linear collider has a large number of readout pads to be connected to conventional electronics just discussed. A new concept has recently been proposed by which the gas amplification is done by a “standard” MPGD, but the endplate is made up of a matrix of Si chips in which the readout electronics is integrated.

This concept offers the possibility of pad sizes small enough to observe individual single electrons formed in the gas and count the number of ionization clusters per unit track length, instead of measuring the integrated charge collected. Initial tests using Micromegas[16] and GEM foils[17] mounted on the Medipix2 chip provided two-dimensional images of minimum ionizing track clusters. A modification of the Medipix2 chip (called TimePix) to measure also the drift time is under development within the framework of EUDET[11]. Also a first working integrated grid has been produced[18]. Latest results and happenings will be described in Section 5.6 below.

4.8 Software

A significant effort on simulation was done for earlier detector studies[1]. Much more is needed now since data from the prototypes is being analyzed and the overall detector design is undergoing reiteration. Software work is being pursued by the groups listed under the LC-TPC/LP workpackages in Section 3.2 (which is almost all of them). In addition Victoria[20], Desy[21] and Carleton[22] are developing track-fitting tools for understanding the TPC resolution, and these are being utilized by all groups studying data from the prototypes. Also simulation work is on-going to understand the TPC calibration and performance in the presence of backgrounds (see also the Appendix). The work will be coordinated in future within the framework of the LC-TPC/LP workpackages.

5 R&D results

In this section, examples of preliminary results from measurements and studies performed by a number of different groups are shown. The results cover the areas of exploring the basic operational parameters of an MPGD-equipped TPC and measurements of the resolution achievable under different conditions. Since only a few examples can be presented here, more details may be found in the publications by the individual groups and in reports delivered at linear collider workshops, most recently the LCWS06 workshop in March 2006[23].

5.1 Operational experiences with MPGD TPCs

The prototypes mentioned in Section 4.3 have been operated over extended periods of time. As expected cleanliness plays an important role in preparing the chambers for operation, to avoid dust and other foreign substances from compromising the HV performance of the devices.

When designing a MPGD equipped system special care has to be taken to minimize the stored energy in the end plates. The GEM or Micromegas systems form essentially large capacitors relative to the readout plane. Under some circumstances enough energy can be stored in these capacitance to destroy the MPGD in the case of a sudden discharge. This can be avoided by subdividing the MPGD into smaller areas, and properly protecting them from the power supply to avoid sudden surges in the current.

As experience has grown, reliable operating conditions have been established for GEM and Micromegas by the groups.

5.2 Gas studies

As explained on several occasions, the gas choice for the LC-TPC is crucial. Gases being investigated are variations of standard TPC gases, e.g., Ar(93%)CH_4(5%)CO_2(2%)–“TDR” gas, Ar(95%)CH_4(5%)–“P5” gas, Ar(90%),CH_4(10%)–“P10”, Ar (90%)CO_2(10%), Ar (95%)Isobutane(5%) and Ar(97%)CF_4(3%). In general the properties measured are in

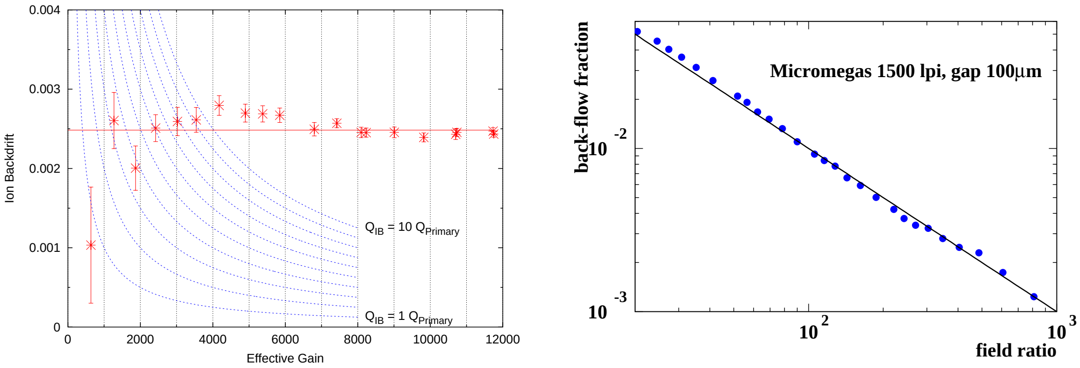

Figure 1: Left: Relative ion backdrift versus effective gain for optimized triple-GEM voltages. Right: Ion backflow fraction as measured with Ar-10%CH_4 for Micromegas (the line is the expectation from the inverse-field-ratio law).

good agreement with the predictions by the Magboltz simulation[24].[13] Thus gas simulations can be used to help design the LC-TPC. Further design issues related to the chamber gas are found in the Appendix, Item 4.

5.3 Ion backflow

In order to minimize the impact of ion feeding back into the drift volume, a required backdrift suppression of about 1/gasgain has been used as a rule-of-thumb, since then the total charge introduced into the drift volume is about the same as the charge produced by the primary ionization. As stated in the introduction, MPGDs lend themselves naturally to the intra-train un-gated operation at the ILC since they can operate with a significant suppression of the number of back-drifting ions. However the levels of backdrift suppression achieved during our R&D program are probably not sufficient, as seen in the following section (5.3.1).

5.3.1 Charge transfer studies in MPGD structures

In the case of GEMs, using the parametrisation of the charge transfer coefficients as a function of the electric fields, the ion backdrift is calculated as a product of charge transfer coefficients and single GEM gain factors. By scanning the whole parameter space and calculating the ion backdrift at every point, minima in ion backdrift can be found. Using this method, an ion backdrift of 2.5 per-mille has been achieved in a magnetic field of 4T.

The results are seen in Fig. 1-left[14], which shows the dependence of the minimum ion backdrift on the effective gain of the triple GEM structure. For each data point, all GEM voltages and fields were optimized and the resulting ion backdrift was measured. The relative ion backdrift is almost independent of the gain. Therefore, the choice of low gasgain (if the signal to noise ratio is acceptable) will lead to a low absolute ion charge drifting back into the drift volume. However the desired 1/gasgain supression would only work for gasgains of 400 or below, and since the LC-TPC electronics is not yet designed, it is not clear whether the signal/noise ration will be sufficient in this case.

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[13] Some supplies of ArCF_4 have shown discrepancies which still need to be understood.

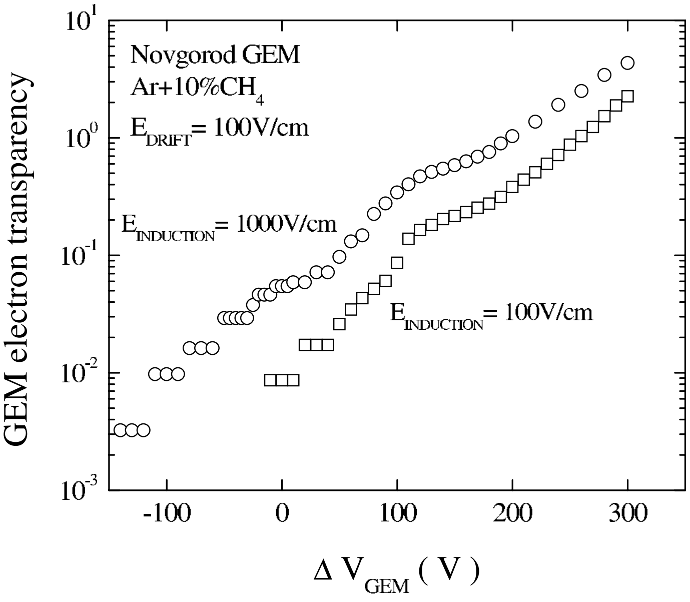

Figure 2: Studies towards understanding the procedures for gating using a GEM layer: here a measurement of the tranparency for electrons.

For Micromegas[25], the TPC drift and the multiplication region see very different electric fields, with a ratio of typically 300 between them. Charge which arrives from the drift region within one mesh gap is compressed to a funnel of a size of typically only a few microns. The electrons then diffuse on their way towards the readout plane. The typical diffusion for electrons in the high field region between the mesh and the readout plane is around 15 μm (depending on field and gas), which is large compared to the size of the funnel. The ions are mostly produced towards the end of the electron drift, i.e., when the electrons are well diffused. The ions drift back following the electric field lines. Only those few which have been produced within the funnel will go back into the drift region, the rest will be absorbed by the mesh. It has been shown that the expected ion backflow can be described simply by the inverse ratio of the two fields. This simple model has been tested successfully in a number of experiments. The results, Fig. 1-right[6], show that measurements and theory agree very well. From the plot it can be seen that a total ion backflow of a few times 10^{-3} seems possible. For this case field ratios of around 300 implies a backflow suppression factor of 0.3% which may not be small enough, similar to the case for GEMs above.

5.3.2 Upshot

Since the goal of 1/gasgain will be difficult to achieve and for other reasons discussed in the Appendix, Item 4(c), a gating grid should be foreseen. Gating using a GEM layer may be possible[26]; measurements are underway to understand GEM-gating procedures, as demonstrated in Fig. 2.

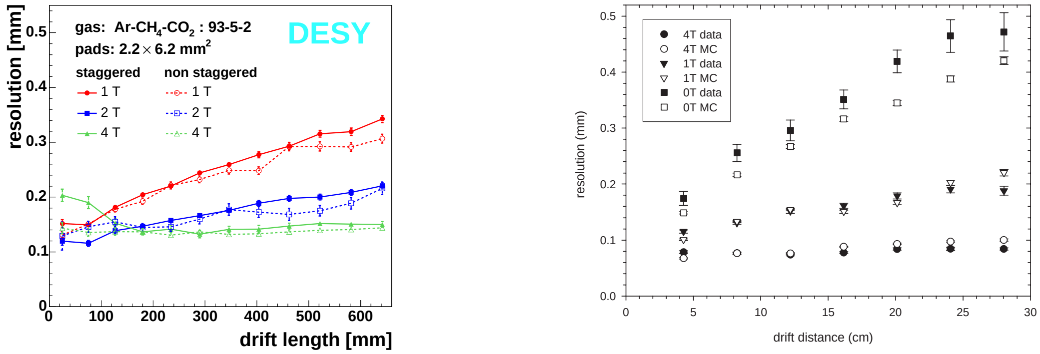

Figure 3: Point resolution measured in a GEM-equipped TPC for different magnetic fields and pad geometries. Left: 93-5-2% ArCH$_4$CO$_2$ (TDR gas), right: 95-5% ArCH$_4$(P5)

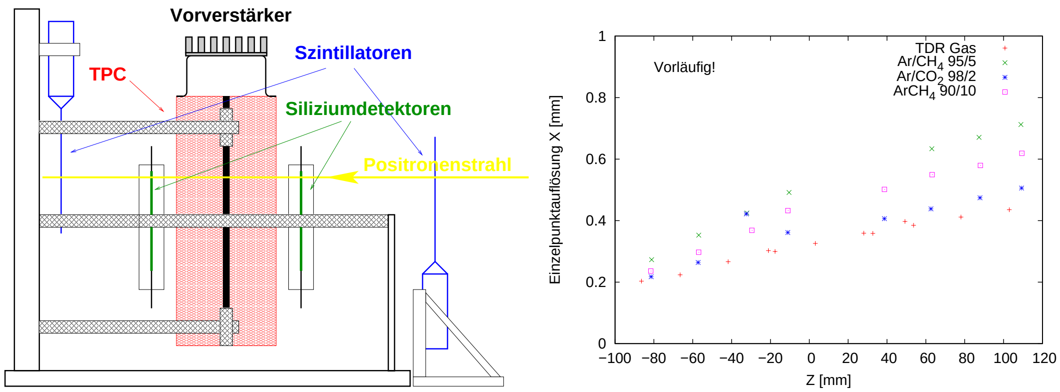

Figure 4: Left: A combination TPC and Si hodoscope. Right: Preliminary measurements from a run at the DESY test beam.

5.4 Resolution studies with MPGDs

One of the central requirements for a TPC at the LC is a good single point resolution. The goal is to reduce this to around 100 μm, which is well below point resolutions reached in previous large TPC. Many measurements have been made over the last year on prototypes with MWPC, GEM and Micromegas gas-amplification endplates.

5.4.1 *GEM*

The results from a measurement[21] using GEMs of the resolution in B-fields of 1T, 2T and 4T and with TDR gas are shown in Fig. 3-left. Another result from [20] but for a P5 gas mixture is presented in Fig. 3-right. The next example in Fig. 4 shows measurements of position resolution in the DESY test beam and 1T magnet using a new setup at Aachen consisting of a prototype TPC together with a silicon detector hodoscope.

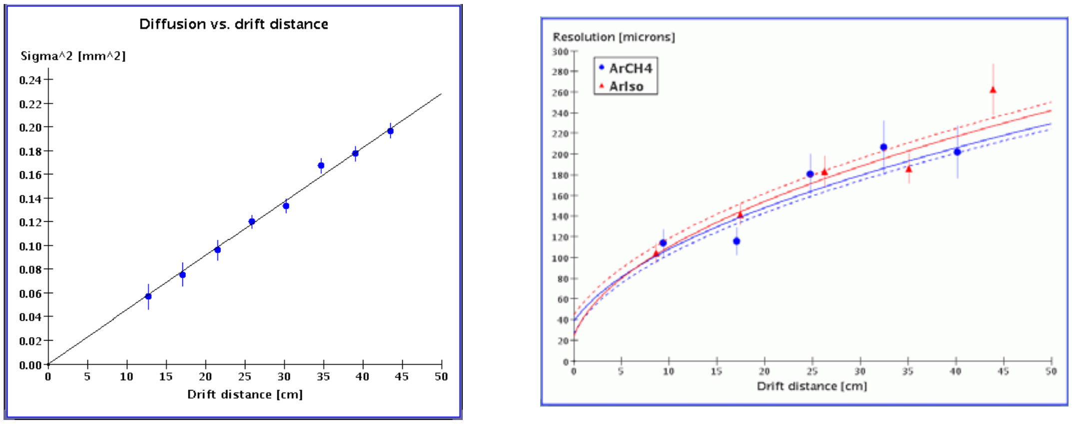

Figure 5: Left: Track r.m.s. width measured with the Micromegas TPC at Saclay at 1T as a function of the drift distance. Right: Resolution measurements (points) using the same chamber for two gases, the fits (lines) and the predictions (dotted lines).

5.4.2 *Micromegas*

Using the test TPC of a diameter of 50cm and a drift length of 50cm, tests have been carried out in a 2.0 T magnet at Saclay with cosmic rays. The recorded tracks are fitted with a circle fit in the $r\phi$ projection, perpendicular to the magnetic field lines. Six out of 10 possible pad rows are included in the track fit, the remaining four are used to estimate the resolution of the system. As measure of the diffusion, the square of the average r.m.s. width (Sigma∧2) (called "pad response" below) versus drift distance is shown in Fig. 5-left. The resolution was measure using many gases, for example Fig. 5-right.

5.4.3 *Another example: MWPC, GEM, Micromegas, resistive foil TPC tests at KEK.*

To provide a comparison and explore the potential improvements using MPGDs a small prototype chamber[12], initially with an MWPC endplate, was built at MPI-Munich and has been tested by a collaboration of American, Asian and European groups (see the author list of this report). This chamber was commissioned at MPI, tested using cosmics at DESY in their 5T magnet and subsequently was exposed to four beam tests at KEK using MWPC, GEM, MicroMegas and resistive-foil technologies (see Section 5.5). (The chamber will be called MP-TPC, for MultiPrototype-TPC, in the following.)

The different techniques of gas amplification were tested with a combination of gas mixtures and read-out pad planes mounted in the MP-TPC using a 4GeV/c π^- test beam; examples are listed in Table 1. The diffusion constant(C_D) is a key parameter to determine a single-point resolution and was measured from using the behaviour of signal-charge spread as a function of drift distance. The point resolution is naively parametrized by $\sigma_{r\phi} = \sqrt{\sigma_0^2 + C_D^2/N_{eff} \times z}$, where, σ_0 is mainly determined by diffusion during gas amplification and by the ratio between signal-charge spread and geometrical pad size, N_{eff} is the effective number of electrons contributing to the resolution as determined by effects of statistics, gain fluctuations and efficiency in amplification, and z is the drift distance. The data obtained are being analyzed and compared to Monte Carlo simulation, preliminary results have been presented at recent conferences related to the ILC (e.g. [23]) and the final results will be published in the near future.

Gas Amplif. method	Typical Gas	Pad Pitch(mm^2)	Magnetic Field(T)
MWPC	TDR, P5	2.3×6.3	0, 1, 4(Cosmic)
GEM	TDR, P5	1.27×6.3	0, 1
MicroMegas w/ and w/o resistive foil	Ar/C_4H_{10}, $ArCF_4$	2.3×6.3	0, 0.5, 1

Table 1: Some of the parameters used for the MP-TPC beam and cosmic ray tests.

The runs were performed in the following order: MWPC (June 2004), GEM (April 2005), Micromegas (June 2005) and MPGDwith resistive foil (October 2005). The resistive-foil results are discussed in the next Section 5.5.

Continuing with the other technologies in reverse order, in the following cases the pads were readout by the Aleph TPC electronics.

A measurement of the diffusion (pad response) with the Micromegas endplate is illustrated in Fig. 6-upper.

In the case of GEM, a triple-GEM stack was used, and an example measurement in the 4 GeV/c π beam is presented in Fig. 6-middle.

For the MWPC version, the MP-TPC had significantly reduced wire-to-wire and wires-to-pads spacing to increase the achievable resolution and two-track separation. The wire readout consisted of a plane of sense wires with a 20μm diameter and spaced with a 2mm pitch. The sense-wire plane was placed 1mm above the pad plane to obtain the best possible resolution. Figure 6-lower shows results obtained with MWPC gas amplification using cosmics at DESY and the test beam at KEK.

Nota bene

Care must be taken in interpreting some of the test beam results, above in Fig. 6 and below in Fig. 9 in the following section (5.5), until the data are better understood. The chambers were running at very high gasgain during the tests, up to order of magnitude larger than targeted for the LC-TPC (see Section 8 Item 4(b)), and extrapolation to the LC-TPC conditions has not yet been done.

5.4.4 *Expected resolution*

For MPGDs in general, the expected resolution has been analytically derived[27]. The results depend on MPGD parameters of course; an example is presented in Fig. 7. This analytical formula, which has been confirmed by test-beam measurements, can be used to help design the LC-TPC.

5.5 Methods to improve the resolution

Various techniques for "spreading the charge" are under study to avoid degradation in the point resolution due to single-pad hits related to short drift distances. As reported at the previous PRC review[6], in the case of GEMs it has been shown that diffusion between the last GEM and the pad plane can defocus the charge cloud to about 0.4 mm width (depending

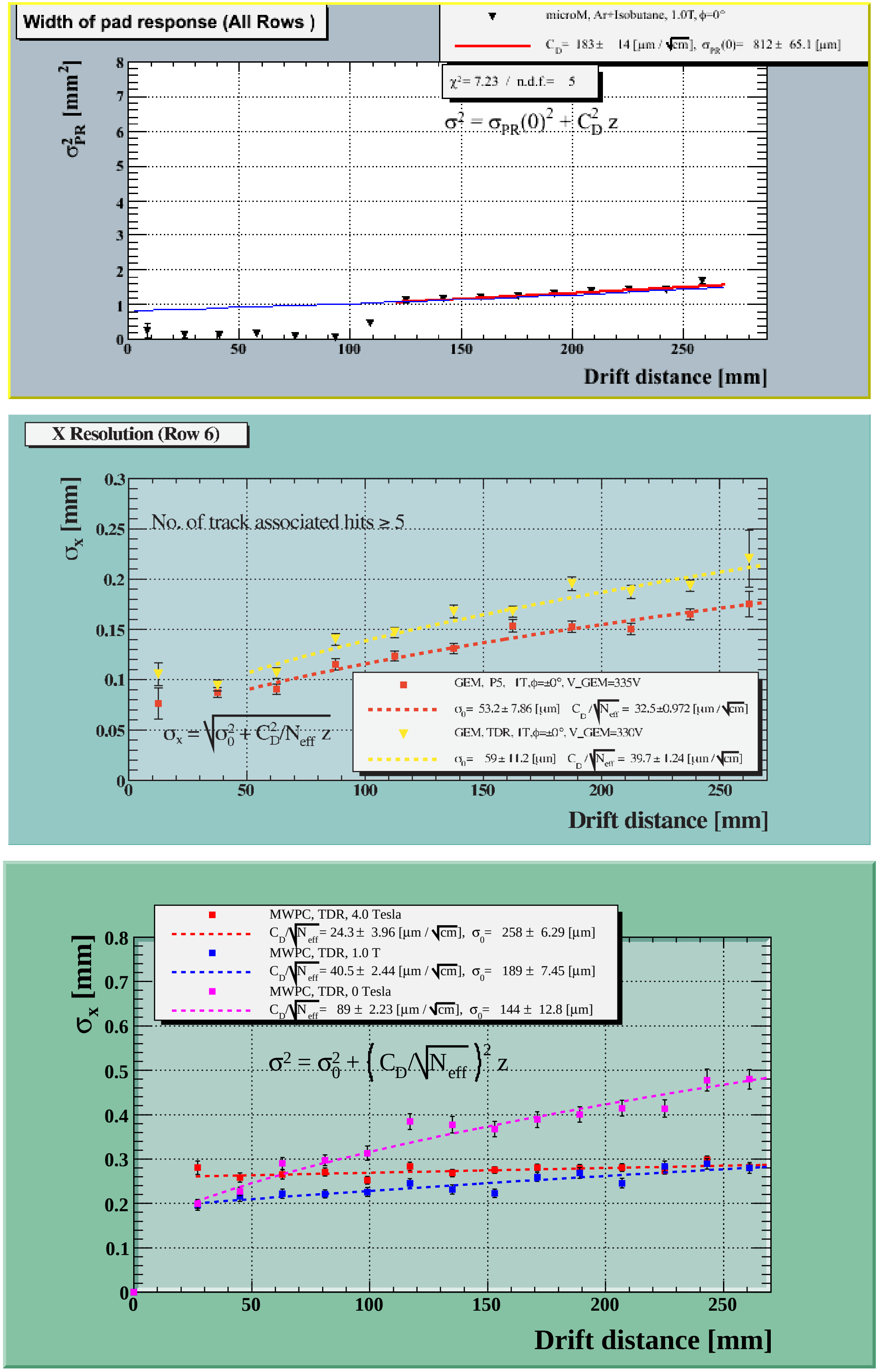

Figure 6: Upper: PRF measured in the 4 GeV/c π beam at KEK using the MP-TPC equipped with a Micromegas endplate (the points go to zero because of the selection criterion of requiring hits with at least 3 pads in order to calculate the charge width). Middle: Measurements using a triple-GEM endplate installed on the MP-TPC in the test beam and 1T magnet at KEK. Lower: MWPC measurements with the MP-TPC using cosmics at DESY and the test beam at KEK.

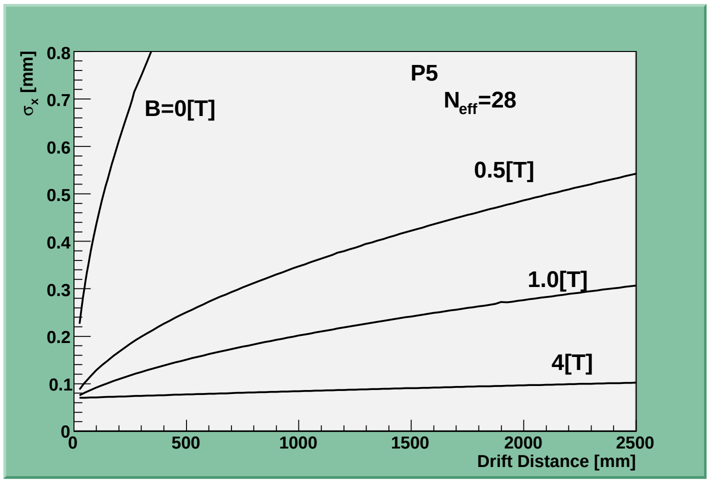

Figure 7: Example of the expected resolution for a TPC with MPGD gas amplification for 0, .5, 1 and 4 T magnetic fields.

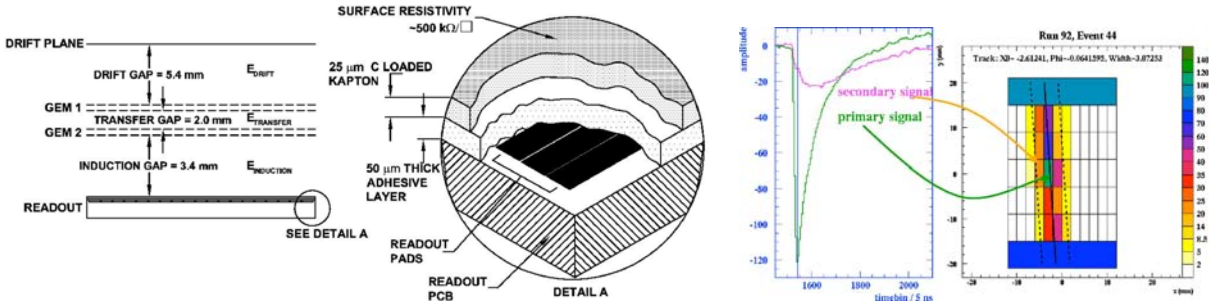

Figure 8: Left: Set up showing application of a resistive foil on a pad plane. Right: Charge dispersion signal on a charge collecting pad and its neighbour for a cosmic ray track in the TPC (Ar-CO_2/90%-10%).

on gas/operating parameters). Further it has been shown that the pad width can be about 3 times that of the cloud and still allow enough charge sharing, but further work is needed to determine the optimal pad size using this defocussing property.

Another possibility also reported previously, the resistive-foil technique, will discussed in some detail next since more tests have been done. In this case a high surface resistivity film, used for the anode, is bonded to the readout padplane with an insulating layer of glue[28], as seen in Fig. 8-left. The resistive anode film forms a distributed two-dimensional RC network with respect to the readout plane. A localized charge arriving at the anode will disperse with a time constant determined by the anode surface resistivity and the capacitance per unit area. With the initial charge covering a larger area with time, wider pads can be used for position determination. First proof-of-principle experiments with a resistive readout plane were performed using a collimated soft X-ray source [22]. To study this method in a real TPC a test TPC was modified described above. The gas amplification was via a double GEM system. Figure 8-right illustrates a TPC charge dispersion pulse for two pads. Both the pulse

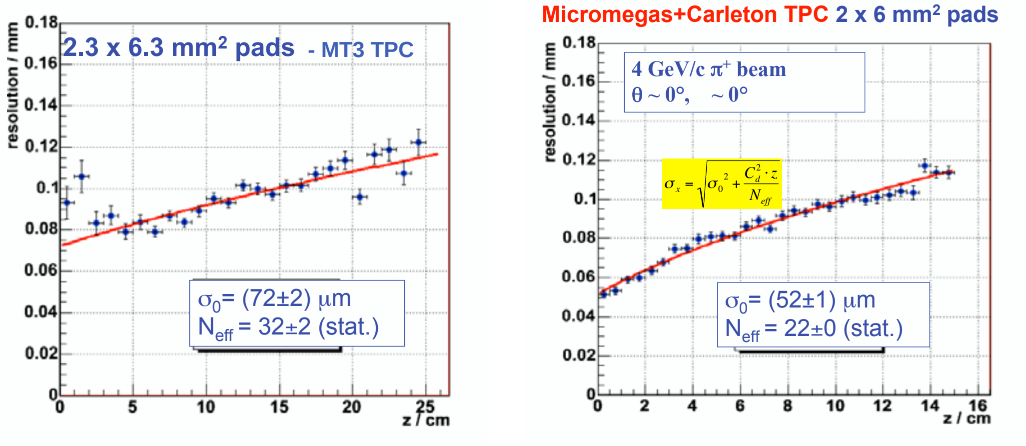

Figure 9: Resolution obtained in the 4 GeV/c pion beam at KEK using the resistive-foil technique. Left: MP-TPC chamber (MT3 in the figure), 2.3mm×6.3mm pad pitch, GEM endplate, P5 gas, B=1T. Right: Carleton chamber, 2mm×6mm pad pitch, Micromegas endplate, ArC_4H_{10} gas, B=1T.

rise time and the decay time depend on the position of the charge with respect to the pad. The charge collecting pad shows a fast signal. The signal on the adjacent pads have a slower rise and decay time.

A detailed simulation has been done to understand the characteristics of charge dispersion signals. Initial ionization clustering, electron drift, diffusion effects, the MPGD gain, the intrinsic detector pulse-shape and electronics effects were included.

Two points are important to note:

-To extract the optimal resolution a detailed knowledge of the pad-response function (PRF) is needed. The pad response function is measured using cosmic muons in separate runs.

-The charge dispersion signals are affected by non-uniformities in the anode resistivity and the capacitance per unit area. Position measured from PRF need to be corrected for local RC distortions. The bias corrections were also determined from the internal consistency of the calibration data set.

This technique was tested earlier with cosmics at Carleton without magnetic field and recently in the 4 GeV/c pion beam at KEK with magnetic field, as discussed above. Several gases were used, Argon with different quenchers: CO_2, CH_4, C_4H_{10} and CF_4. Figure 9 shows two results, left obtained with the MP-TPC, P5 gas and 1T B-field measured using both the Carelton and Aleph readout electronics (the results with which agree), and right obtained with a Micromegas endplate, Argon-isobutane gas and B=1T. All results are still preliminary (see *Nota bene* in Section /refanotherexample above) and in preparation for publication.

In summary the charge dispersion on a resistive anode seems to be a feasible method to improve the single point resolution and bringing it close to the diffusion limit without increasing the number of readout channels.

5.6 Progress towards a TPC with CMOS pixel readout

As reported to the PRC in 2004, first tests were carried out in a small test chamber at Nikhef with a "MediPix" chip, developed for medical applications, and Micromegas gas amplification.

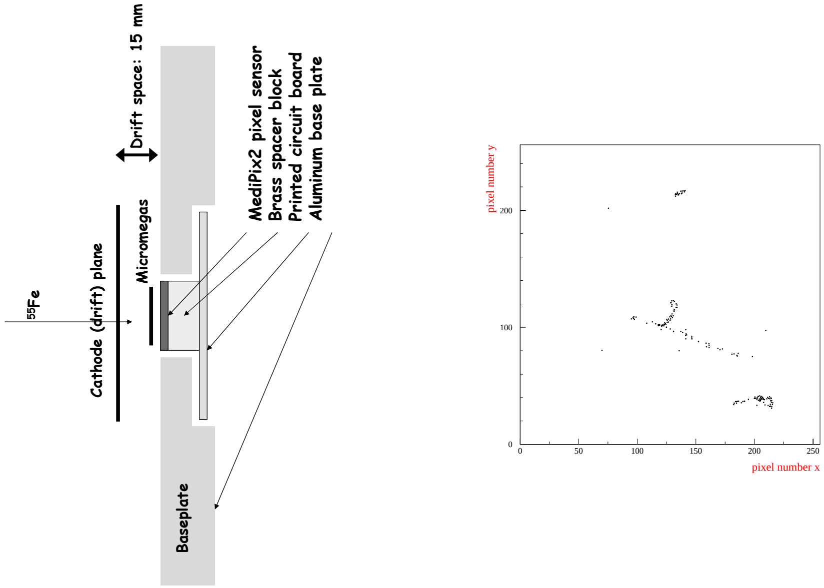

Figure 10: Left: The layout of the chamber with the MediPix2, the Micromegas and the drift gap. Right: Image recorded from the MediPix2/Micromegas prototype TPC showing a cosmic charged particle track together with a δ-electron. The total size of the image is 14.1 $\times$ 14.1 mm^2.

The MediPix chip provided a pixel matrix with amplification and threshold discrimination, but had no time stamping capability. The Si chip for the next step is planned to be a CMOS-based pixel matrix and measure also the drift time. The chip proposed for first test is the *"TimePix"* chip. Each pixel will be equipped with a preamp, a discriminator, a threshold DAC and time-stamping circuitry.

A reminder of the layout at Nikhef is in Fig. 10-left and one of the first tracks recorded in Fig. 10-right. Since the previous PRC in 2004,
-there were problems with consolidation of earlier results with Micromegas[16] on Medipix presumably due to discharges which damaged the Medipix chips. This is in contrast to Freiburg experience with triple-GEM on Medipix (see below), which did not yet damage a single chip.
-There has been qualitative understanding [29] of single electron-detection measurements (from MIPs) by the GEM and Micromegas setups at Freiburg and NIKHEF.
-First results have been achieved using an electron-multiplying grid made in wafer post-processing technology[18].
-A first series of aging measurements of Micromegas has been carried out. The paper is in preparation, and a follow-up of systematic studies is being planned.

The setup at Freiburg[17] recently built using the MediPix chip and GEM gas amplification is seen in Fig. 11-left and Fig. 11-right a track from a radioactive source. What has been achieved is[19], in short:
-stable operation of the system since over one year with the same MediPix chip,
-a cluster density for minimum ionizing particles of 5.8/cm and
-the spatial resolution for a cluster of $\sim$50μm as seen in Fig. 12.

The development of the TimePix chip and the performing of the related R&D has started

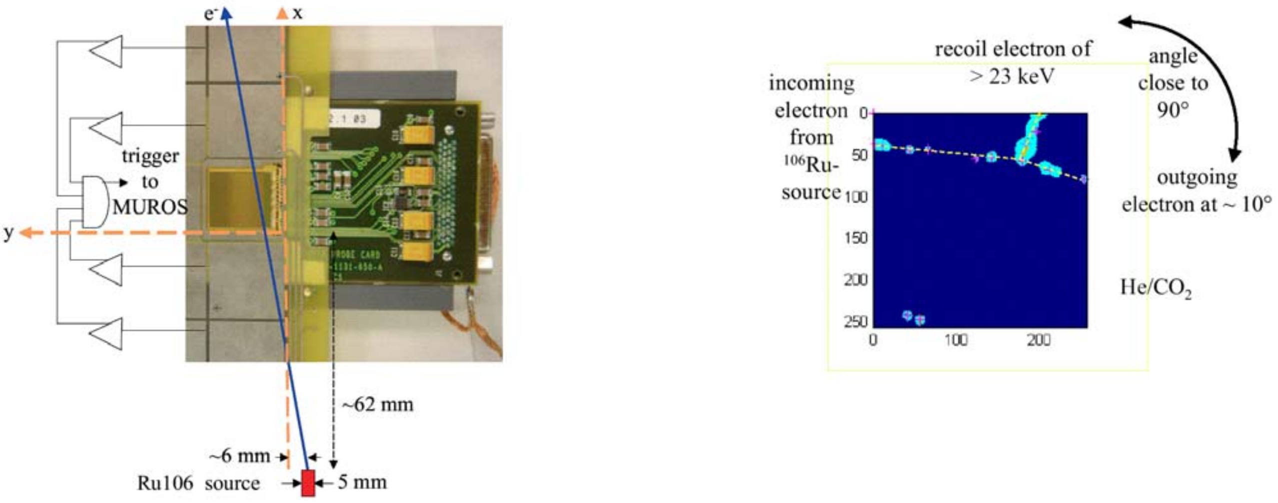

Figure 11: Left: The mounting of a GEM onto the MediPix2 sensor. Right: An electron track from a radioactive source.

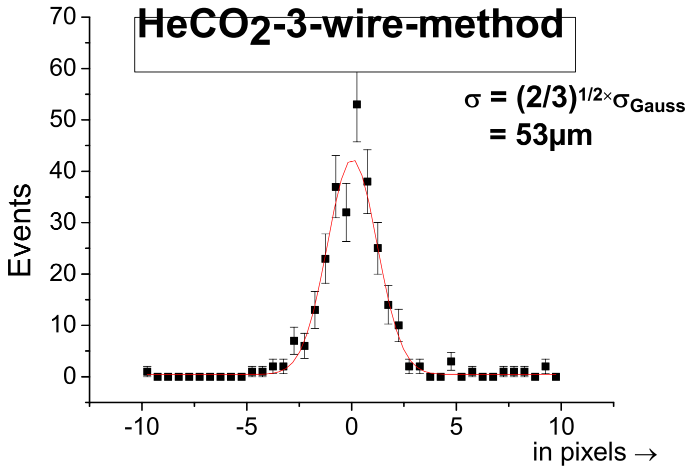

Figure 12: Point resolution analysis of the GEM/MediPix2 set up.

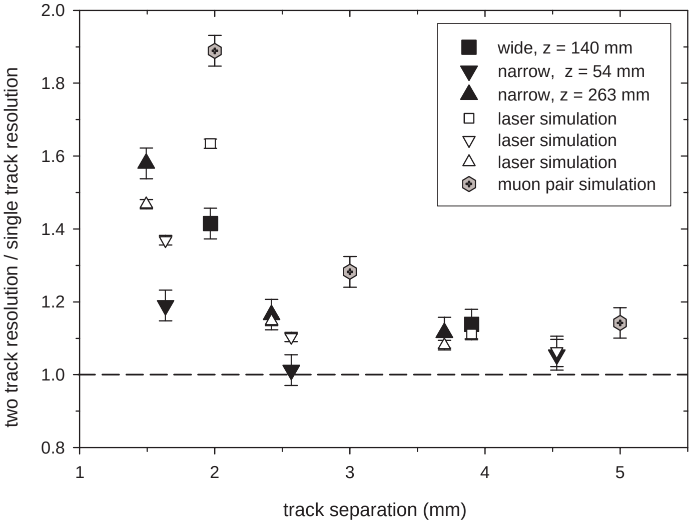

Figure 13: Single row resolution recorded in laser-induced two-track events, as a function of the separation between the two tracks. The horizontal line indicates the resolution for single laser tracks.

within the EUDET framework.

5.7 Double-track resolution studies

The resolution of close-by tracks is very important in the densely collimated jets expected at the linear collider. The specifications call for a possible double-track resolution of a few mm, which is about an order of magnitude better than in previous TPCs.

Measurements of this quantity are underway. Techniques used are test beams on the one hand, UV-laser beams on the other. The approach described here is the use of a UV laser to produce close-by tracks under controlled conditions. First measurements with a laser based system were done in the 5T magnet in the summer of 2004 and reported at the previous PRC. Further investigation was carried out in [20], from which plot of the point resolution on close-by tracks measured with this setup is shown in Fig. 13.

The horizontal line indicates the single row resolution for single tracks, and it is seen that the resolution is unaffected for parallel tracks that are 4mm apart. The resolution degrades somewhat at 2mm separation, so that good track information can be reconstructed from tracks that are separated by about one pad width.

5.8 Track-distortion issues

Studies at Aachen were described for the PRC in 2004[6] where the optimization of GEM voltages was demonstrated. Other measurements was made using the Karlsruhe prototype in a CERN testbeam[30], where a positive-ion build up of about 1 pC/cm^3 was induced. The effect if this ion cloud on charged tracks is being quantified, but it seems that tracks suffer little when passing through such a region with no small gradient.

This very important topic is discussed in detail in the Appendix, Items 6 and 7. It will be a subject to investigate during the TPC R&D program at EUDET[11] to measure these effects and test the tools for making the corrections. In general since the problem has already been solved at LEP[31][32][33][34] to the necessary level of precision, we should make sure these tools are available and apply them to the studies at EUDET.

6 Other needs for future R&D

6.1 Test-beams

Test beams at DESY, KEK and CERN have been used for several studies up to now. In future, the beam at DESY will be the location of the EUDET facility which will be the focus of most of the TPC R&D for the next couple of years. In principle the EUDET facility can move to CERN or Fermilab if the R&D demands it, which is unlikely to be the case for the TPC (but can be the case for the calorimeters).

6.2 Funding situation

With the advent of the EUDET facility, a certain fraction of the finances needed will now be available for the next four years. The EU funding is highly appreciated of course, since it gives the overall effort a foundation to build on for the next phase of R&D. But it is still about a factor of two below the total amount of resources required for carrying out the R&D program. If significant extra resources are missing, the future program will be in danger. At the moment the coherent LP design and R&D planning being set up by the LC-TPC groups is motivated by the optimism that the financial situation will be solved. Therefore the overall funding depends critically on all of the LC-TPC groups, the ones within the EUDET consortium and the extra-EUDET groups, obtaining funding in addition to that provided by EUDET.

7 Conclusion

The LC-TPC groups after four years of concerted effort have accumulated a large body of data and experience with the operation of TPCs equipped with MPGDs. The basic feasibility of using MPGDs in a TPC could be demonstrated.

Currently the participating groups are in the process of finalizing first systematic investigations of the single-point and double-track resolutions. Several methods are under study to readout the large number of channels required, including a proposal to directly couple a CMOS pixel sensor to the readout plane of a TPC.

In the future the work will concentrate on the design, building and operation of a series of larger prototype-endplates within the LC-TPC/LP project at the EUDET facility, to test not only the basic feasibility but also detailed engineering questions. All these should be answered before a real design of a TPC for the ILC detector can be started.

The LC-TPC groups expect that this second phase of the work will take around three to four years and will require substantial funding in addition to what will be provided by the EUDET initiative.

The LC-TPC groups request the DESY PRC to continue supporting its program and its quests for additional funding from the international community. The DESY group within the LC-TPC consortium asks the PRC to approve its continued participation in this effort and requests adequate support to maintain its role.

8 APPENDIX–Overview of design issues for the LC-TPC

8.1 The Basic Concept of the LC-TPC

General arguments for a TPC as main tracker are as follows. The tracks can be measured with a large number of ($r\phi$,z) space points, so that the tracking is continuous and the efficiency remains close to 100% for high multiplicity jets and in presence of large backgrounds. It presents a minimum of material to particles crossing it. This is important for getting the best possible performance from the electromagnetic calorimeter, and to minimize the effects due to the $\sim 10^3$ beamstrahlung photons per bunch crossing which traverse the detector. The comparatively moderate $\sigma_{singlepoint}$ and double-hit resolution are compensated by the continuous tracking and the large volume which can be filled with fine-granularity coverage. The timing is precise to 2ns (corresponding to 50 μm/ns drift speed of tracks hooked up to the z-strips of a Si detector with 100μm pitch), so that tracks from different bunch crossings or from cosmics can readily be distinguished via time stamping.

To obtain good momentum resolution and to suppress backgrounds near the vertex, the TPC has to operate in a strong magnetic field. It is well suited for this environment since the electrons drift parallel to $\vec{B}$, which in turn improves the two-hit resolution by compressing the transverse diffusion of the drifting electrons (FWHM$_T \leq 2$ mm for Ar-10%CH$_4$ gas and a 3T magnetic field). Non-pointing tracks, e.g. for V^0 detection, are an important addition to the particle flow measurement and help in the reconstruction of physics signatures in many standard-model-and-beyond scenarios. The TPC gives good particle identification via the specific energy loss, dE/dx, which is valuable for many physics analyses, electron-identification and particle-flow applications. The TPC will be designed to be robust and at the same time easy to maintain so that an endplate readout chamber can readily be accessed or exchanged in case of accidents like beam loss in the detector.

Two additional properties of a TPC will be compensated by proper design. The readout endplanes and electronics present a a small but non-negligible amount of material in the forward direction; the goal is to keep this below 30%X$_0$. The $\sim$50μs memory time integrates over background and signal events from 160 ILC bunch crossings at 500 GeV for the nominal accelerator configuration; this is being compensated by designing for the finest possible granularity: the sensitive volume will consist of several$\times 10^9$ 3D-electronic readout voxels (two orders of magnitude better than at LEP). It has been estimated to result in an occupancy of the TPC of less than 0.5% from beam backgrounds and gamma-gamma interactions[1]. (See below for further discussion.)

8.2 Design issues.

There are many aspects for the layout of the LC detector and its subdetectors. The detector has to be designed globally to cover all possible physics channels, and the roles of the subdetectors in reconstructing many of these channels are highly interconnected. For the TPC, the issues are performance, size, endplate, electronics, gas, alignment and robustness in backgrounds.

- 1.Resolution expected/needed The requirements for a TPC at the ILC are summarized in Table 2. A main question to answer is: what should the resolution be for the overall tracking? This will define how many silicon layers are needed. Present folklore says that overall $\delta(1/p_t) \sim 5 \times 10^{-5}$/GeV/c will be sufficient, as defined mainly by the e$^+$e$^- \rightarrow HZ \rightarrow H\ell\ell$ channel used for measuring the Higgs production rate. This resolution is achievable with

Table 2: Typical list of performance requirements for a TPC at the ILC detector.

Size	$\phi = 3.2 - 4.1$m, L $= 4.2 - 4.6$m
Momentum resolution	$\delta(1/p_t) \sim 10^{-4}$/GeV/c (TPC only; × 2/3 when IP included)
Solid angle coverage	Up to at least $\cos\theta \sim 0.98$
TPC material budget	$< 0.03\mathrm{X}_0$ to outer fieldcage in r $< 0.30\mathrm{X}_0$ for readout endcaps in z
Number of pads	$\sim 1.3 \times 10^6$ per endcap
Pad size/no.padrows	$\sim$ 1mm×6mm/$\sim$200
$\sigma_{\mathrm{singlepoint}}$ in $r\phi$	$\sim 100\mu$m (average over driftlength)
$\sigma_{\mathrm{singlepoint}}$ in rz	~ 0.5 mm
2-track resolution in $r\phi$	< 2 mm
2-track resolution in rz	< 5 mm
dE/dx resolution	< 4.5 %
Performance robustness	$> 95\%$ tracking efficiency (TPC only), $> 98\%$ overall tracking
Background robustness	Full precision/efficiency in backgrounds of ca. 20% occupancy, whereby simulations estimate $< 0.5\%$ for nominal backgrounds.

inner-silicon tracking and a TPC performance given in Table 2. If for physics reasons, the overall tracking accuracy should be better, a larger TPC and/or more silicon layers should be envisaged.

- 2.Endplate The two TPC endplates have a surface of about 10 m^2 of sensitive area each. The layout of the endplates, i.e. conceptual design, stiffness, division into sectors and dead space, has been started. For this the question arises as to how to make odd-shaped MPGDs that will be needed. In general, the readout pads, their size, geometry and connection to the electronics and the cooling of the electronics, are all highly correlated design tasks related to the endplates. As stated in Section 8.1, the material budget for the endcap and its effect on Ecal for the particle-flow measurement in the forward direction must be minimized. More details are covered in the next item.

- 3.Electronics For the readout electronics, one of the important issues is the density of pads that can be accomodated while guaranteeing a thin, coolable endplate. The options being studied are (a) standard readout (meaning, as in previous TPCs) of several million pads or (b) pixel readout of a few hundred times more by using CMOS techniques.

(a) Standard readout:
Pad sizes under discussion are, for example, 2 mm times 6 mm (the TDR size[1]) or 1 mm times 6 mm which has found to be better as a result of our R&D experience. A preliminary look at the FADC, CCD or switched-capacitor-array approach using 130 nm technology indicates that even smaller sizes like 1 mm times 1 mm might be feasible (in which case charge-spreading would not be needed). In all of these cases there are between 1.5 and 20 million pads to be read out. An alternative to the FADC-type is the TDC approach (see [5][11]) in which time of arrival and charge per pulse (via time over threshold) is measured. If it turns out that the material budget requires larger pads, then the resistive-foil technique[22] is an option to maintain the point resolution.

(b) CMOS readout:

A new concept for the combined gas amplification and readout is under development. In this concept[5] the MPGD is produced using wafer post-processing technology on top of a CMOS pixel readout chip, thus forming a thin integrated device of an amplifying grid and a very high granularity endplate, with all necessary readout electronics incorporated.

- 4.Chamber gas This issue involves (a) gas choice, (b) ion buildup and (c) ion feedback.

(a) Gas Choice.

The choice of the gas for a TPC is an important and central parameter.

When choosing a gas a number of requirements have to be taken into account. The $\sigma_{\text{singlepoint}}$ resolution achievable in $r\phi$ is dominated by the transverse diffusion, which should be as small as possible. Simultaneously a sufficient number of primary electrons should be created for the point and dE/dx measurements, and the drift velocity at a drift field of a few times 100 V/cm should be about 5 cm/μs or more. The hydrogen component of hydrocarbons, which traditionally are used as quenchers in TPCs, have a high cross section for interaction with low energy background neutrons which will be crossing the TPC at the ILC[1]. Thus the concentration of hydrogen in the quencher should be as low as possible, to minimize the number of background hits due to neutrons. An interesting alternative to the traditional gases is a Ar-CF_4 mixture. These mixtures give drift velocities around $8 - 9$ cm/μs at drift field of 200 V/m, have no hydrocarbon content and have a reasonably low attachment coefficient at low electric fields. However at intermediate fields (~5-10 kV/cm), as are present in the amplification region of a GEM or a Micromegas the attachment increases drastically, thus limiting the use of this gas to systems where the intermediate field regions are of the order of a few microns. This is the case for Micromegas, but its use has not been tested thoroughly for a GEM-based chamber. Whether CF_4 is an appropriate quencher for the LC-TPC is not yet known and is being tested as a part of our R&D.

(b) Ion Build-up.

The issues are the ion build-up at the surface of the gas-amplification plane and the ion build-up in the drift volume.

At the surface of the gas-amplification plane vis-a-vis the drift volume, during the bunch train of about 1 ms and 3000 bunch crossings, there will be few-mm thick layer of positive ions built up due to the incoming charge, subsequent gas amplification and ion backdrift. An important property of MPGDs is that they suppress naturally the backdrift of ions produced in the amplification stage. This layer of ions will reach a density of several tens of fC/cm^3 depending on the background conditions during operation. Intuitively its effect on the coordinate measurement should be small since the drifting electrons incoming to the anode only experience this environment during the last few mm of drift. In any case, the TPC is planning to run with the lowest possible gas gain, meaning of order 10^3, in order to minimize this effect.

In the drift volume, a positive ion density due to the primary ionization will be built up during about 1s (the time it takes for an ion to drift the full length of the TPC), will be higher near the cathode and will be of order fC/cm^3 at nominal occupancy ($\sim$ 0.5%). The tolerance on the charge density will be established by our R&D program, but a few × fC/cm^3 is well below this limit.

(c) Ion backdrift and gating.

In order to minimize the impact of ion feeding back into the drift volume, a required backdrift suppression of about 1/gasgain has been used as a rule-of-thumb, since then the total charge introduced into the drift volume is about the same as the charge produced in the primary ionization. Not only have these levels of backdrift suppression not been achieved during our

R&D (see Section 5.3.1, but also this rule-of-thumb is misleading. Lower backdrift levels will be needed since these ions would drift as few-mm thick sheets through the sensitive region during subsequent bunch trains. Even if a suppression of 1/gasgain is achieved, the overall charge within the sheets will be the same as in the drift volume so that the density of charge within a sheet will be one to two orders of magnitude greater than the primary ionization in the total drift volume. How these sheets would affect the track reconstruction has to be simulated, but to be on the safe side a backdrift level of $<<$ 1/gasgain will be desirable. Therefore, since the backdrift can be completely eliminated by a gating plane, a gate should be foreseen, to guarantee a stable and robust chamber operation. The added amount of material for a gating plane is small, $< 0.5\%X_0$ average thickness. The gate will be closed between bunch trains and remain open throughout one full train. This will obviate the need to make corrections to the data for such an "ion-sheets effect" which could be necessary without inter-train gating.

- 5.The fieldcage The design of the fieldcage involves the geometry of the potential rings, the resistor chains, the central HV-membrane, the gas container and a laser system. These will have to be laid out for sustaining at least 100kV at the HV-membrane and a minimum of material. Important aspects for the gas system are purity, circulation, flow rate and over-pressure. The final configuration depends on the gas mixture, which is discussed above, and the operating voltage which must also take into account the stability under operating conditions due to fluctuations in temperature and atmospheric pressure. For alignment purposes (see next two items) a laser system will be foreseen, either integrated in the fieldcage[10] or not[31].
- 6.Effect of non-uniform field

Non-uniformity of the magnetic field of the solenoid will be by design within the tolerance of $\int_{\ell_{\rm drift}} \frac{B_r}{B_z} dz < 2$mm used for previous TPCs. This homogeneity is achieved by corrector windings at the ends of the solenoid. At the ILC, larger gradients could arise from the fields of the DID (Detector Integrated Dipole) or anti-DID, which are options for handling the beams inside the detector in case a larger crossing-angle optics is chosen. This issue was studied intensively at the 2005 Snowmass workshop[32], where it was shown that the TPC performance will not be degraded if the B-field is mapped to 10^{-4} relative accuracy and the calibration procedures outlined in the next point (Item 7) are followed. Based on past experience, the field-mapping gear and methods should be able to accomplish this goal. The B-field should also be monitored since the DID or corrector windings may differ from the configurations mapped; for this purpose the option of a matrix of Hallplates and NMR probes mounted on the outer surface of the fieldcage is being studied.

Non-unformity of the electric field can arise from the fieldcage, backdrift ions and primary ions. For the first, the fieldcage design, the non-uniformities can be minimized using the experience gained in past TPCs. For the second, as explained above, the backdrift-ions can be minimized at the MPGD plane using low gasgain and eliminated entirely in the drift volume using gating. The effect due to the third, the primary ions, is due to backgrounds and is irreducible. As discussed above, the maximum allowable electrostatic charge density has to be established, but studies by the STAR experiment[10] indicate that up to 1 pC/cm^3 can be tolerated, whereas at nominal occupancy it will be of order fC/cm^3. This will be revisited by the LC-TPC collaboration by simulation and by the R&D program, Section 3.2.

- 7.Calibration and alignment The tools for solving this issue are Z peak running, the laser system, the B-field map, a matrix of Hallplates/NMR probes and the Si-layers outside the TPC. In general about 10/pb of data at the Z peak will be sufficient during commissioning to master this task, and typically 1/pb during the year may be needed depending on the backgound and energy of the ILC machine. A laser calibration system will be foreseen which can be used to understand both magnetic and electrostatic effects, while a matrix of Hallplates/NMR probes may supplement the B-field map. The z coordinates determined by the Si-layers inside the inner fieldcage of the TPC were used in Aleph[33] for drift velocity and alignment measurements, were found to be extremely effective and will thus be included in the LC-TPC planning. The overall tolerance is that systematics have to be corrected to 30μm throughout the chamber volume in order to guarantee the TPC performance, and this level has already been demonstrated by the Aleph TPC[32].

- 8.Backgrounds and robustness The issues here are the primary-ion charge buildup (discussed above) and the track-finding efficiency in the presence of backgrounds, which will be discussed here. There are backgrounds from the accelerator, from cosmics or other sources and from physics events. The main source is the accelerator, which gives rise to gammas, neutrons and charged particles being deposited in the TPC at each bunch crossing[34]. Preliminary simulations of these under nominal conditions[1] indicate an occupancy of the TPC of less than about 0.5%. This level would be of no consequence for the LC-TPC performance, but caution is in order here. The experience at LEP was that the backgrounds were much higher than expected at the beginning of the running (year 1990), but after the simulation programs were improved and the accelerator better understood, they were much reduced, even negligible at the end (year 2000). Since such simulations have to be tuned to the accelerator once it is commissioned, the backgrounds at the beginning could be much larger, so the the LC-TPC should be prepared for much more occupancy, up to 10 or 20%. The TPC performance at these occupancy levels will hardly deteriorate due to its continuous, high 3D-granularity tracking which is still inherently simple, robust and very efficient with the remaining 80 to 90% of the chamber.

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